Reprinted from MONTHLY WEATHER REVIEW, Vol. 111, No. 5, May 1983
American Meteorological Society
Printed in U. S. A.

Duration of Convective Events Related to Visible Cloud, Convergence, Radar and Rain Gage Parameters in South Florida

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(Manuscript received 2 September 1981, in final form 20 January 1983)

ABSTRACT

The time interval between initiation of surface convergence and the subsequent response of visible cloud growth to this convergence was examined for nine cases of convection that occurred over the FACE 1973 and 1975 mesonetworks in south Florida. Clouds ranged in size from small echoes with a few towers to merged lines or large clusters of towers, but they met a series of observational criteria that specified them as belonging to a similar set of clouds, and were not representative of the entire range of clouds in the area. Visible clouds first formed 10 to 55 min after the associated surface convergence began, and grew rapidly upward 20 to 100 min after convergence started.

This highly variable response could be understood better by taking into account the duration of the cloud, which is defined as the time from first surface convergence to complete dissipation. The same nine cases were examined as were chosen initially for the visible cloud study. When duration was considered, first visible cloud response occurred at an average of 15% through the cloud duration, and rapid upward cloud growth at 36%. Other parameters derived from divergence, radar- and gage-measured rainfall also tended to cluster within specific portions of the total duration of the cloud. The data for each event for the nine clouds are presented and described in terms of the cloud duration.

1. Introduction and background

In the past, photogrammetric studies have related visible cloud growth to radar, gage and synoptic data. However, there appears to be no earlier examination of the time interval between the start of surface convergence and the development of new visible clouds forming directly over the same convergence region. Plank (1969) related Florida cloud population distributions to peninsular-scale patterns, but not on a cloud-by-cloud basis. Orville (1965) studied the initiation of individual cumuli with stereo photogrammetry and attributed their growth to forcing by mountain ridges interacting with the ambient flow, but had no surface convergence data. Other researchers have used photogrammetry to consider various aspects of cloud growth, but not in relation to surface convergence, due to a lack of photo or wind data on the cloud scale. A study of the role of surface convergence in forcing clouds directly overhead has been performed with data collected during the Florida Area Cumulus Experiment (FACE) and is part of this report.

The original purpose of the research was to investigate the linkage between convergence and cloud formation during the early stages of cloud growth. However, in the initial phase of the study, a large variation was found in this time interval, by up to a factor of five. The research was then expanded, in the second phase of the study, to seek a reason for the variation.

It was found that the highly variable time interval could be explained by considering the duration of the same cumulus systems as the clouds that were chosen for their visible cloud views. Short convergence/cloud-response times were associated with short-lived cloud systems, and long intervals related to long-lived systems. The shorter-lived cloud systems were smaller and less intense than the long-lasting ones. This second portion of the research goes beyond the Thunderstorm Project (Braham, 1952), where cumulative rainfall amount was shown to be associated with cumulative storm duration in a regular fashion during a storm's lifetime. From the FACE mesonetwork, a larger variety of data specific to the cloud itself is examined by relating several cloud development milestones to duration of the cloud systems.

2. Data and procedures

The data used in the study were obtained during the Florida Area Cumulus Experiment (FACE) in the southern portion of the peninsula. All cases but one were from FACE 1975; the data were collected in the mesonetwork shown in Fig. 1. Time-lapse cameras in 1975 were located at the three Doppler sites and

[1] A portion of this research was conducted while the authors were at the National Hurricane and Experimental Meteorology Laboratory, Coral Gables, FL 33146.

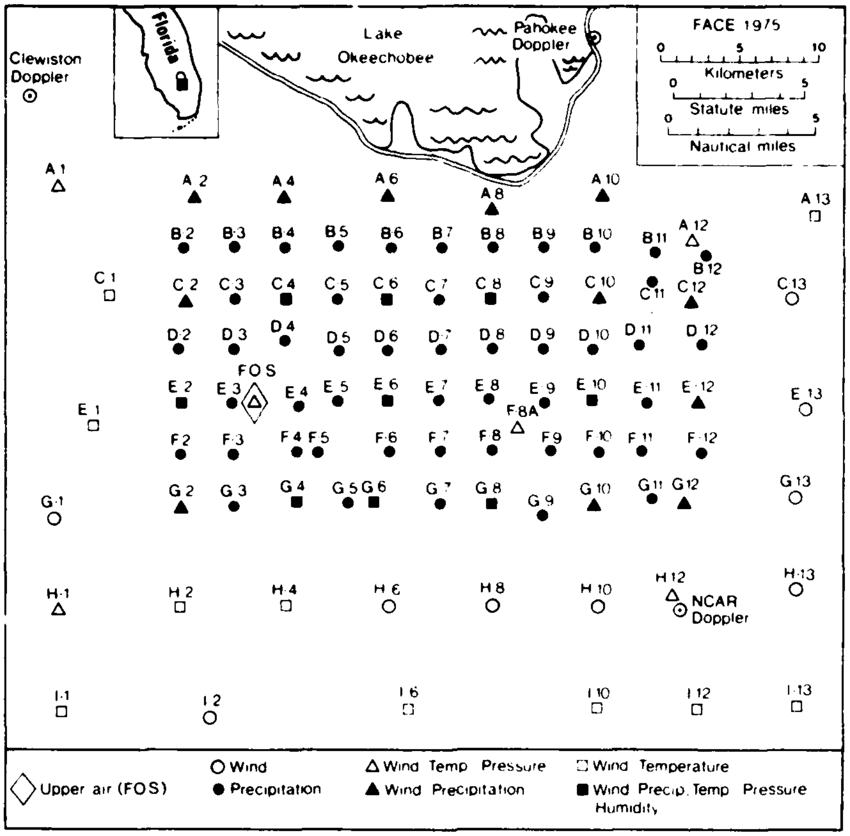

FIG. 1. FACE 1975 mesonetwork. Time-lapse cameras were located at all three Doppler radar sites and at the Field Observing Site (FOS). The wind network covered 1440 km^2.

the Field Observing Site (FOS) in the west-central network. One case was from FACE 1973 when the mesonetwork was located somewhat east of, but overlapping, the 1975 area. Hand-held photos but no time-lapse pictures were taken for the 1973 case. The Miami WSR-57 radar is located about 100 km from the center of the mesonetwork. The rain gages and wind stations in 1975 are shown in Fig. 1.

Time-lapse photographs in 1975 were taken on 16-mm color film looking toward the center of the mesonetwork at a rate of one frame per 5–7 seconds. For the study of visible cloud response to convergence, the first step was to identify periods when a significant but isolated new cloud formed and grew in the cameras' views. Next, the radar data were searched for an isolated echo that was strong enough to be identified with a distinct convergence center and visible cloud. In most situations, the cameras were not directed toward the exact location where the isolated echo was starting to grow, other clouds obscured the view, the cameras were not operating, or, most commonly, the very early stage of cloud formation was not identifiable or capable of being related simply to a surface convergence center. For large clouds, the cloud field was often too distant from the camera to be certain of the location, and therefore a correspondence with the radar or convergence event could not be made at the early stage of new growth which was needed to define the start of surface convergence. For small clouds, the area of visible clouds during the early growth stage was not large enough to be detected readily with the wind station spacing (6.4 km average).

There were nine cases, however, where subject clouds grew in the mesonetwork and could be included in the sample. Smaller clouds in this set had several definable towers and single-cored radar echoes throughout their lifetime. Larger clouds were merged lines or clusters of towers which grew into echoes with several cores. In all cases, there was a distinguishable convergence center, smaller than the 1440 km^2 mesonetwork area, which was separate from other convergence patterns in south Florida. If the convective entity was not separable with the radar or convergence data, the case was not included in this study. Convergence areas and radar echoes in these nine cases ranged in size from a small portion (~10%) to most of the total area of the 1440 km^2 mesonetwork. The nine echoes selected for this paper belong to the upper third of the size distribution of echoes in this

area; however, they do not include echoes comprising the largest 5% of the distribution (Wiggert *et al.*, 1981). Lopez (1978) has shown that the largest 5% of the echoes account for 80% of the rainfall in the eastern Atlantic. Since rainfall in both the eastern Atlantic and Florida is largely generated by convection, a similar distribution of rainfall amount versus echo size may also occur in the FACE network.

3. Visible cloud response to convergence

The growth response of visible clouds directly over the area where first convergence occurred was described in terms of three parameters called Events A, B, and C. Event A was the time of first convergence, Event B was the time of first visible cloud response, and Event C was the time of rapid upward growth of the visible cloud.

It is recognized that prior to Event A used in this study, other parameters could be measured that produce the first convergence which was considered the start of these systems. Pressure perturbations, outflows from other clouds, etc., could be detected prior to first convergence in some cases. Here, the research began with convergence for all cases regardless of its source.

First convergence (Event A) was determined to the nearest 5 min from several of the products available for studies of convergence and rainfall on these days. First, the daily time profiles of area average divergence and weighted convergence (defined in Watson *et al.*, 1981) for the full 1440 km^2 mesonetwork were examined to find the 5-min period when the background, prevailing convergence increased to a stronger convergence value which was identifiable as related to a specific convective entity. Watson *et al.* showed that an increase in convergence of 25×10^{-6} s^{-1} in 10 min over the total network is the crucial parameter to relate to rainfall, and that concept was used for the larger and longer-lasting clouds whose convergence covered a significant portion of the network. Second, for the smaller clouds, area divergence quantities and their changes were calculated at 5-min intervals in the specific portion of the network where the cloud was located, such as a quadrant, because total network data were not sufficiently sensitive to isolate the cloud. Third, maps of divergence and streamlines over the mesonetwork were made at 5-min intervals to specify the time and locate the regions of development of small clouds. The combination of these 3 steps to define the start of a convergence event was not difficult to use for determining Event A for the nine cases. All other cases were omitted when the start of convergence was unclear from the data.

Visible cloud initiation (Event B) was often rather easy to determine to the nearest 5 min from the time-lapse film. In several cases, there were no clouds in the surface convergence area; the time of first cumulus appearance was considered to be the response to the prior convergence. In the other situations, a disorganized and essentially random field of small non-raining, shallow cumulus clouds grew horizontally and vertically to become organized and clustered in a rather short time; cloud bases merged and became noticeably darker and harder at this stage. Some of these changes were from random cumuli to a new line, and others were to a new cluster of cloud elements. The area of the visible cloud initially was smaller, in general, than the convergence area over which the cloud formed. Later, as the cloud became mature or was dissipating, the mature cloud's radar echo grew to an area similar to the area of the originating convergence zone, as shown in the case study of Holle and Maier (1980).

The time of rapid upward visible cloud growth (Event C) was also rather easily found from the same film. It can best be described as the time when several or many towers are simultaneously growing upward very rapidly. At this time the cloud line or complex is passing into the stage where it is apparent that the cloud definitely will produce rainfall. Event C was found to the nearest 5 min.

Table 1 shows results of the analysis of nine clouds whose initial growth stages were well defined. For estimated (Est.) times, the discrepancy usually was ±5 min from the given time. Data for the FACE 1973 case of June 15 were compiled from the analysis by Holle and Maier; the FACE 1975 case of August 19 has been the subject of research by Cunning *et al.* (1982). The interval from first convergence (Event A) to the time of initial organization of the visible cloud system (Event B) ranged from 10 to 55 min and av-

TABLE 1. Times of Events A, B, and C for nine cloud entities in FACE 1973 and 1975 mesonetworks. Events B and C are expressed in min after Event A.

Date	Time of first convergence Event A	Visible cloud response Event B (min)	Rapid upward growth of visible clouds Event C (min)
15 June 1973	1425 EDT	Est. 35	Est. 50
08 Aug. 1975	1645	Est. 20	45
12 Aug. 1975	Est. 1720	20	60
13 Aug. 1975	Est. 1425	Est. 25	75
18 Aug. 1975	Est. 1345	15	70
19 Aug. 1975	1450	55	100
20 Aug. 1975	Est. 1545	25	75
25 Aug. 1975 (A)	1305	Est. 20	45
25 Aug. 1975 (B)	Est. 1415	10	20
Average time (min)	0	25	60
Normalized time (%)	0	15	36

eraged 25 min, with a standard deviation of 11 min. It was another 35 min until the rapid upward growth stage (Event C) was reached, which was 60 min on the average after Event A (standard deviation of 13 min). The interval between convergence and visible cloud growth would be shorter for clouds that never produced radar echoes. During the growth stage of the nine subject clouds, variability in the time intervals can be partially explained by such factors as the rate of increase in convergence while the cloud grows (Watson *et al.*, 1981). They also found that convergence changes of a given amount produced different cloud responses when stratifications were made by humidity aloft, stability, and low-level wind speed.

TABLE 2. Events used to study storm duration in FACE mesonetworks.

Event	Description	Data
A	First convergence above background levels	Mesonetwork winds
B	Visible clouds first appear or are no longer randomly distributed	Time lapse photos
C	Visible clouds start rapid upward growth	Time lapse photos
D	First radar returns from cloud entity	Radar
E	Maximum convergence at cloud entity	Mesonetwork winds
F	First rain on ground	Rain gages and/or photos
G	Maximum radar rainfall from cloud entity	Radar
H	Maximum gage-measured rain from cloud	Rain gages
I	Maximum divergence at cloud	Mesonetwork winds
J	Complete dissipation	Radar and/or photos

4. Time history of storm events normalized to duration

The preceding lags of visible cloud growth after the initiation of surface convergence varied from case to case by as much as a factor of 5. Not shown in Table 1 is the fact that longer time intervals tended to be associated with longer cloud lifetimes and larger storms. To take this effect into account, the times of Events B and C were normalized to the total duration of the storm system. Event A was chosen as the start of the system's lifetime (0%), and the time of dissipation (100%), called Event J, was found from radar or time-lapse photos. When the nine cases were normalized on this scale, Event B occurred at an average of 15% (bottom line, Table 1) through the lifetime of the cloud entity, and Event C was at 36%.

It was apparent from these results for visible clouds that normalizing the events to cloud duration was useful in understanding the variations in time lags between the individual cases. Other specific events (Table 2) were then sought which could be identified for the same nine cases that were studied for visible cloud response. Since surface wind, rain gage and radar data were readily available over the duration of cloud entities originally identified for the visible cloud lag study, six more parameters were chosen to relate to duration for the second part of the research. These milestones were shown to occur in a similar order for south Florida convection in the conceptual model proposed by Ulanski and Garstang (1978) over a range of cell sizes. Here the investigation will be on the relationship between the time of these events relative to the duration of the system; no direct predecessor of this study is apparent. Two wind-related milestones were chosen: times of maximum convergence (Event E) and maximum divergence (Event I) associated with the cloud system. They were determined with the same types of information as that given earlier for first convergence (Event A). Another pair of events was derived from the Miami radar: times of first radar returns from the subject cloud (Event D) and maximum radar-estimated rainfall from the cloud entity (Event G). The latter was a volume measure for the entire echo; the time of the maximum was for the entire echo found from 1) the time history graph of radar reflectivity for the entire mesonetwork, which may include other echoes, and 2) from maps showing the magnitude of the relevant echo's core intensity at 5-min intervals. The center of the radar beam was typically about 1 km above the surface in the mesonetwork. Finally, rain gage data were considered for two situations. Event F refers to the time of the first rain on the ground, which was detected either by gages or from time-lapse photos of the cloud. Subject clouds occurred principally over the uniform gage network (Fig. 1) so that gage density was not critical for finding Event F. Event H was the time when gages measured the maximum rainfall from the cloud (15-min accuracy at times), although there were several instances when clouds moved out of the gage and camera network. Finally, Event J is the time of complete dissipation from radar or photos.

Normalized times for Events A to J are listed in Table 3 and diagrammed in Fig. 2. Average duration (Events A–J) for the nine cloud entities was 161 min. The individual Events B and C, referring to visible cloud development, are shown by Table 1 in minutes and by Table 3 in normalized times. The first radar returns (Event D) also occurred 36% through the cloud system, the same as Event C, and in some situations occurred earlier than Event C. (Numbers in

TABLE 3. Normalized times, as percent of total duration, when events A to J occurred for nine cloud entities in FACE. Times are normalized to storm duration (right column), which extended from Event A as 0% to Event J as 100%. Normalized averages and standard deviations are at bottom of table.

Date	Event A	B	C	D	E	F	G	H	I	J	Duration (min)
15 June 73	0	29	38	54	(38)	58	58	69	77	100	130
8 August 75	0	14	31	(24)	34	38	45	41–52	59	100	145
12 August 75	0	12	38	(36)	(34)	41	62	missing	69	100	160
13 August 75	0	14	42	(41)	(67)	50	72	69–78	86	100	180
18 August 75	0	9	44	(34)	47	(41)	47	56–66	75	100	160
19 August 75	0	23	43	45	51	51	(62)	55–57	81	100	235
20 August 75	0	13	39	39	39	41	62	(54–62)	69	100	195
25 August 75 (A)	0	15	33	33	(22)	41	81	missing	(56)	100	135
25 August 75 (B)	0	9	18	(14)	27	32	55	missing	59	100	110
Average (%)	0	15	36	36	40	44	60	61	70	100	161
σ (%) ($n-1$ method)	0	7	8	12	14	8	11	10	11	0	38

parentheses in Table 3 refer to events that were out of time order from the average sequence.) After another 4% of the duration (6 min), maximum convergence occurred (Event E), followed 6 min later by first rain on the ground (Event F); the times for events C, D, E and F are quite similar and are not deemed to be significantly different. Note that the time interval between first radar and first gage detection of rainfall averaged 8% of the duration, or 13 min. This time interval is similar to the results of Holle and Maier (1980), and extends the results of Watson *et al.* (1981) from their study of convergence using radar-estimated rainfall to results using gages. The mature stage of the cloud systems is shown by the next three events (diagrammed as descending in Fig. 2). On the average, maximum radar-estimated rainfall (Event G) was at about the same time (60%) as maximum gage-measured rainfall (Event H) at 61%. Maximum surface divergence (Event I) occurred at 70% of the storm's duration. The dissipation stage from that point to the complete disappearance of the cloud entity (Event J) was another 30% of the cloud lifetime, compared with 15% from first convergence to first presence or organization of visible clouds. In summary, the highly variable times found from the study of visible clouds, and shown in Table 3 for the other events, are found

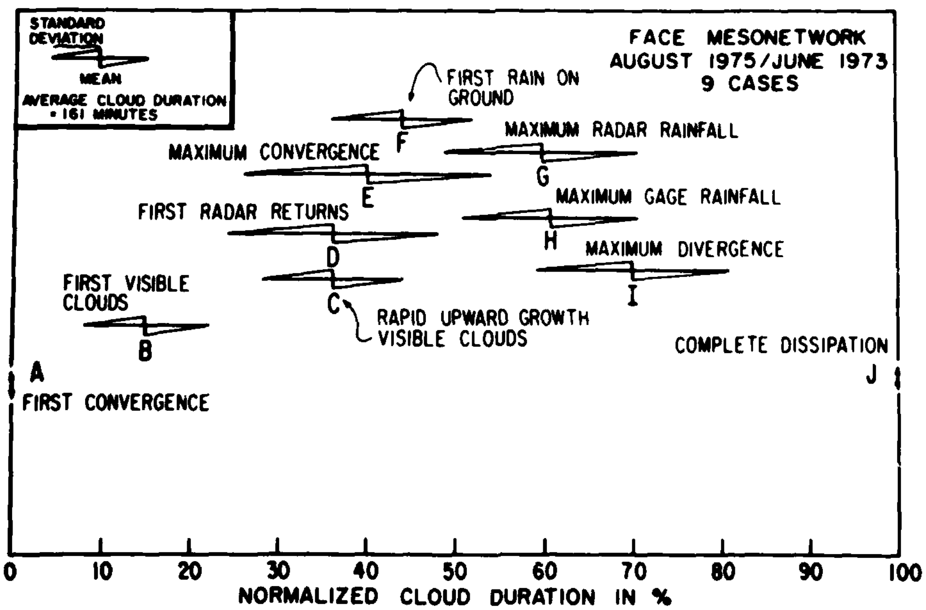

FIG. 2. Normalized cloud duration in % for Events A to J during nine cases of cloud entities growing in FACE mesonetwork during June 1973 and August 1975. Mean % of each event at center of diamond; standard deviation shaded to either side.

to be rather well organized by taking duration into account. The times when the events occur are not distributed uniformly over the total duration of the cloud, but tend to cluster in a specific portion of the normalized cloud duration, and this tendency helps explain the large variability in the time intervals before normalization.

5. Discussion

There were two major conclusions from this study. First, visible cloud development lagged convergence initiation over a wide range of time intervals. The average was 25 min from first convergence to first organization of the cloud field, and another 35 min passed, on the average, until the clouds began a rapid upward growth stage. This is apparently the first study to quantify these time intervals. Second, these variable time responses could be explained partially by taking into account the duration of the entire cloud system. Short periods from convergence initiation to an event such as visible cloud formation, rainfall or radar echo initiation tended to be associated with short times until the demise of the cloud system, and conversely for long periods and long-lived systems.

The lag of visible cloud development after convergence was sought from an additional source of time-lapse photography in a mesonetwork in Illinois during the 1979 VIN program (University of Virginia–Illinois State Water Survey–NOAA). It proved impossible to define these early events sufficiently well to add to the sample presented here for FACE. The principal difficulties were advection into the mesonetwork of existing clouds, convergence apparently aloft rather than at the surface, large and complex convergence and cloud fields, and motion of growing clouds across the camera view. The events that were identified usually occurred in the same order in Illinois as in Florida; however, there were no cloud sequences that could be followed completely in the VIN network to comprise additional cases for the present study.

This study of visible cloud reaction to surface convergence has lead to a more general examination of cloud milestones related to duration. Specific events within a cloud lifetime tended to cluster within rather narrow portions of the total duration of a cloud. How long these clouds lasted also was well-correlated ($r = .92$) with the rainfall production by the cloud entities, although this sample consists of a narrow range of sizes and types of clouds, as detailed earlier. Based on this study, the lag of visible clouds behind surface convergence has been specified for a small number of south Florida clouds, and should be studied elsewhere to see how well the conclusions apply. In addition, the role of duration in delineating the timing of cloud development should be examined further with larger data sets to find how well such features as the early stages of radar echoes or satellite images can provide information on how long the convective system will last.

Acknowledgments. Our thanks are extended to two NOAA employees, Mr. Tony Barnston and Mr. James Hansen, for advice and calculations related to this paper. This research was supported by the Atmospheric Research Section, National Science Foundation and the Army Research Office, Department of Defense, under NSF Grant ATM-78-08865.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 15529.12-GS	2. GOVT ACCESSION NO. AD-A134664	3. RECIPIENT'S CATALOG NUMBER N/A
4. TITLE (and Subtitle) Duration of Convective Events Related to Visible Cloud, Convergence, Radar and Rain Gage Parameters in South Florida		5. TYPE OF REPORT & PERIOD COVERED Reprint 6. PERFORMING ORG. REPORT NUMBER N/A
7. AUTHOR(s) Ronald L. Holle Andrew I. Watson		8. CONTRACT OR GRANT NUMBER(s) ARO 20-78
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Research Laboratories/NOAA Boulder, CO 80303		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS N/A
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE May 83 13. NUMBER OF PAGES 6
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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